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PROPERTIES OF OPTICAL MATERIALS IN SPACE

Fred W. Paul[1]

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ABSTRACT: A program has been established to provide a central clearing house for information about the effects of space environment on the optical and other physical properties of optical materials. Information is being collected and organized on the effects of space environment on refractive index, dispersion, transmittance, reflectance, thermal expansion coefficient, Young's modulus, birefringence, and yield and breaking points of all materials of interest for the transmission or reflection of optical radiation in space.

In technical areas where information about the behavior of materials does not exist a program of laboratory investigations will provide the required information. In preparation for some in-house studies of materials at very low temperatures and also during exposure to a charged particle flux an experiment has been devised and instrumented to provide measurement of dimensional changes and refractive index changes at several wavelengths. The essence of the method is the use of Fabry-Perot interferometry to measure independently the dimensions of the sample of material and the optical path length through the material.

[1]Test and Evaluation Division, Goddard Space Flight Center, Greenbelt, Md. 20771

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Introduction

The behavior of optical materials and components and systems in space is of primary interest to the designers and users of space borne optical devices. Questions often arise, at all phases of a program, i.e., design, manufacture and use, as to what effect the environment will have on a particular element. During the years of space studies a substantial body of knowledge about this subject has been developed. It has often been difficult to locate the required information to answer a question about what behavior can be expected. The program which is being described in this paper is an effort to collate and codify this knowledge to make it more readily available to those who need it.

The environment of space is not a single definable thing. Depending on where in space one intends to operate there may be a variety of atomic ions, or a concentration of electrons, or trapped radiation belts, or solar wind and a variety of electromagnetic radiation, and low or high temperature. There are also environmental components which are carried with the spacecraft, for example condensible vapors or a nuclear power plant. It may or may not be desirable to include the environments of manufacturing, test, prelaunch and launch in this discussion. The material properties that are to be included are transmittance, absorptance, emissivity, reflectance, scattering, refractive index, dispersion, birefringence, thermal expansion coefficient. Also Young's modulus, hardness, yield point and breaking point for all materials of interest for the transmission and reflection of radiation in space. If it is decided that photovoltaic devices and various detectors should be included, then the electric properties of these devices and materials must also be included. The complexity of this

subject, which is illustrated by the above remarks, is one of the reasons that answers to questions about the behavior of materials in space are difficult to find. Another factor is that the determination of what material will serve for a specific mission is often a routine engineering task which is forgotten as soon as it is accomplished. However, there are some notable exceptions to this, e.g., the vigorous and effective program on spacecraft coatings by the Thermophysics Specialist Group of AIAA and ASTM has established a solid and well publicized basis for choice of materials and methods of evaluating new materials.

Information Center

A program has been established at GSFC to collect and interpret and interrelate information about optical materials suitable for use in space borne systems. The optical properties like transmittance and refractive index and the other physical properties like moduli and expansion coefficients will be recorded and the effect on these properties of exposure to the various factors of the use environment will be determined. In instances where available publications such as periodic literature, meeting reports, and conference proceedings do not provide adequate information studies will be established to fill the gaps. This program is expected to produce extensive and adequately cross referenced bibliographies. In addition it is planned that several summaries or position papers will be issued which will provide comparative information on candidate materials for specific applications. It is intended that the bulk of the literature research, extraction and compiling of pertinent information and the studies to provide new information will be done under contract, probably with research institutes or academic departments. In this period of shrinking budgets this program has not competed successfully for funds with some of the more glamorous items like manned flight and orbiting observatories. Nonetheless a small start has been made as an in-house task and some interesting items about

materials behavior in space or in simulated space environment have been noted.

There is a very extensive and well-known literature about radiation effects on optical materials (for example, Reference 1) which has evolved from nuclear studies and from solid state physics. It is usually time-consuming to extract from this large volume of literature information pertinent to a particular space application problem. Bibliographies of materials directly related to space applications (Reference 2) are very helpful and more of them are needed. There are also some very useful general articles (References 3, 4) which elucidate the problem areas and the practically possible solutions. In addition there are a number of studies of more restricted scope which confine their attention to a certain class of materials or a single environmental factor, (References 5,6,7,8) or similar restriction. Information in this form is the easiest to use, provided that the circumstances involved in the engineering application fall within the scope of the study. There are also two handbooks (References 9, 10) which provide guidance for the use of optical materials in space.

It would not be appropriate at this time when but a small fraction of the available and desirable information has been collected, to draw conclusions or to summarize. However there are one or two items which might be mentioned briefly. One is that reflecting surfaces appear to endure the space environment very well. Canfield, Hass and Waylonis (Reference 11) showed that aluminum mirrors overcoated with magnesium fluoride will stand years of space exposure without loss of reflectance. Pittman, et al (Reference 7) and Gunter, et al (Reference 12) have observed that diffraction gratings, both original rulings and replicas, show only very small adverse effects of exposure to a simulated space environment. The chief hazard to reflecting surfaces seems to be contamination by deposits of condensible materials. Gunter also found that some mirror substrate materials are better than others in resisting change of optical figure at high doses of electrons. Among fused quartz, pyrex, borosilicate crown glass, synthetic fused silica, and Cervit, the

synthetic fused silica retained its shape best and also showed least discoloration due to the irradiation. Another item of interest is the study of changes of refractive index of optical glass due to gamma rays (Reference 13) and electrons (Reference 14). Malitson, et al observed substantial changes in refractive index, as much as a few parts in the fourth decimal place due to irradiations. The refractive index showed continuing instability for long periods after the irradiation. Unfortunately this study was left incomplete due to lack of funds. A third item that might be mentioned is the conclusion reached by Heath and Sacher (Reference 6) that magnesium fluoride, barium fluoride and synthetic sapphire will provide the most stable high transmittance for ultraviolet wavelengths. These are but a few of the interesting bits of information about the behavior of optical materials in space. They serve to illustrate that many useful and sometimes unexpected results have appeared in the literature. Perhaps the above few paragraphs may serve to introduce the literature search and organization of information which is planned. I would like now to describe a modest in-house laboratory program which is being undertaken to provide information in an area which seems not to be well covered elsewhere.

An Experiment

Malitson, Dodge and Gonshery have reported[13,14] on the effects of penetrating radiation on the refractive index of some optical glasses. Gunter, et al[12], have observed changes in optical figure of diffraction gratings and their substrate material due to doses of 1 MEV electrons. It seems that it would be interesting and useful to know at what rate these changes occur during exposure to the radiation environment and whether the changes in refractive index and figure exhibit any rapid increases or decreases when the radiation field is removed. In order to provide the required information a system has been built which permits continuous measurement of refractive index and physical dimensions and optical figure during exposure of materials to

penetrating radiation. The essence of the method is use of interferometry to measure index of refraction and dimensions during exposure. This is done without mechanical contact of the measuring system with the sample to be measured.

The method being used is illustrated in Figure 1. Plates A and B are arranged as a Fabry-Perot interferometer. The sample is inserted part-way between the F-P plates and is held parallel to them. By patch-work coating of the sample four different interference patterns are obtained. The first pattern, formed by the rays indexed (1), is used to determine the interferometer spacing, d, by conventional Fabry-Perot procedures[15]. Rays (2) are used to determine the optical path length between the interferometer plates when the rays pass through the sample. This length is $d + (n - 1)t$ where n is the refractive index and t is the thickness of the sample. Rays (3) and (4) are used to determine respectively the distance between the upper interferometer plate and the top surface of the sample, and between the lower interferometer plate and the bottom of the sample. The difference between the distances found from rays (3) and (4) and (1), when appropriate corrections are made for phase changes on reflection and for thickness of the coatings, gives the thickness of the sample, t.

To consider the required measurements in a little more detail the following equations may be written:

$$P_1\lambda = 2d + 2\delta_1 \qquad (1)$$

$$P_2\lambda = 2[d + (n - 1)t] + 2\delta_1 \qquad (2)$$

$$P_3\lambda = 2L_1 + \delta_1 + (\delta_3 + \epsilon_3) \qquad (3)$$

$$P_4\lambda = 2L_2 + \delta_1 + (\delta_4 + \epsilon_4) \qquad (4)$$

Where P_1, P_2, P_3, P_4 are the experimentally found orders of interference for the four sets of rays. λ is wavelength. d is the F-P interferometer spacing. δ_1 is the phase change on reflection at

the F-P plates, assumed to be the same for both plates. n is refractive index and t is the thickness of the sample. L_1 and L_2 are the distances between the Fabry-Perot plates and the nearest surface of the sample. δ_3 and ϵ_3 are the phase change on reflection and the thickness of the patch coating in the upper side of the sample and δ_4 and ϵ_4 are the corresponding quantities on the lower side.

If equation (1) is subtracted from (2) one has

$$P_2\lambda - P_1\lambda = 2(n - 1)\, t \tag{5}$$

The phase change drops out and the left hand side contains only measurable quantities. If we subtract the sum of (3) and (4) from (1) we have

$$P_1\lambda - (P_3\lambda + P_4\lambda) = 2d - 2(L_1 + L_2) - (\delta_3 + \epsilon_3 + \delta_4 + \epsilon_4) \tag{6}$$

Since

$$d - (L_1 + L_2) = t, \text{ we have}$$

$$P_1\lambda - (P_3\lambda + P_4\lambda) = 2t - (\delta_3 + \epsilon_3 + \delta_4 + \epsilon_4) \tag{7}$$

Once more the left side contains measurable quantities. However, to evaluate the δ's and ϵ's on the right side a separate experiment is required. For this fringes of equal chromatic order will be used as described by Bennett[16]. In this method the coated area for which δ and ϵ are to be determined will be partially overcoated with an opaque layer of aluminum. The equal chromatic order fringes which are formed by interference between reflected light from the double coated surface and a uniformly coated flat comparison surface can be analyzed to determine values for both δ and ϵ of the coated area for which these quantities are to be measured. Inserting all the measured values in equation (7) yields a value for t. Putting this value of t in equation (5) yields a value of n. This process is repeated for as many wavelengths as necessary.

The principal application envisioned for this

method of measurement is in situ measurement in intense penetrating radiation fields. For several reasons, however, the first application will be measurements at reduced temperatures. For one thing, a new method always required "shaking down" and the available radiation facilities are so heavily loaded with work that to take up facility time for shake-down operations is undesirable. Another factor is that information about the performance of some ultraviolet transmitting materials at low temperatures has not been published and such information has been requested for planning purposes on some space missions. Also the measurement of refractive index and thermal expansion coefficient of some twenty optical glasses by Molby[17] and the thermal expansion of some infrared transmitting materials by Browder, et al[18] provide a convenient means of comparing results obtained with the new method with those obtained by older methods.

For the low temperature work a liquid helium cryostat is used which is provided with both electrical heaters and pumping tubes so that temperature can be stabilized at points both below and above the boiling point of helium at atmospheric pressure. The sample is attached to the liquid helium chamber by a massive OFHC copper block to which the sample is attached with indium solder to provide good thermal contact. The Fabry-Perot etalon, which consists of fused silica plates separated by an invar spacer ring, is held in position by thin stainless steel strips with adjusting screws so that the etalon plates can be maintained parallel to the surfaces of the sample which is positioned between the two plates, as shown in Figure 1. The cryostat has two fused silica windows through which observations of the fringe pattern are made.

The cryostat is evacuated by a turbomolecular pump with a large liquid nitrogen cooled trap between pump and cryostat followed by two room temperature right angle bends and finally a right angle bend at the liquid nitrogen shield wall of the cryostat. Pumpout and backfill operations are carefully managed to reduce the likelihood of contamination of the cryostat. Monitor mirrors are frequently inserted in place of the interferometer and are

measured for contamination effects by the method recommended by Hass and Hunter[19]. No contamination has been detected in three months of operation.

The interferometer is illuminated by an argon ion laser, which provides five strong lines in the range 476 nm to 514 nm. On occasion when longer wavelength information is desired a helium-neon laser radiating at λ633 nm is substituted. The fringe patterns are photographed either with a view camera or with a Hilger constant deviation spectrometer with camera attachment. To avoid confusion among the several interference patterns that exist due to the various rays shown in Figure 1, an aperture is used which limits the area of the interferometer which is recorded by the camera to dimensions of the order of 1 mm x 3 mm for any particular photograph. The chosen area is moved sequentially to obtain pictures of the fringe pattern formed by rays (1), then rays (2), etc., as shown in Figure 1. A set of four pictures, which can be taken in an elapsed time of 5 to 10 minutes, gives the necessary information for determining the refractive index at several wavelengths and the mechanical thickness of the sample for a specific temperature. The temperature of the specimen is measured with a thermocouple embedded in the specimen but outside the portion used for optical measurements. A series of measurements with several thermocouples simultaneously has shown that the temperature measured at the thermocouple is not significantly different from that where the optical measurements are made.

The apparatus which has been described has been completely assembled. Preliminary experiments have been run on temperature sensing, on determination of phase changes on reflection, on contamination and on photography of the Fabry-Perot fringes. The first complete experiments to determine refractive index and linear thermal expansion coefficient at temperatures between room temperature and liquid temperature will be done this month. Further work will include additional materials in a temperature range of interest to space missions followed by a transfer to a radiation facility.

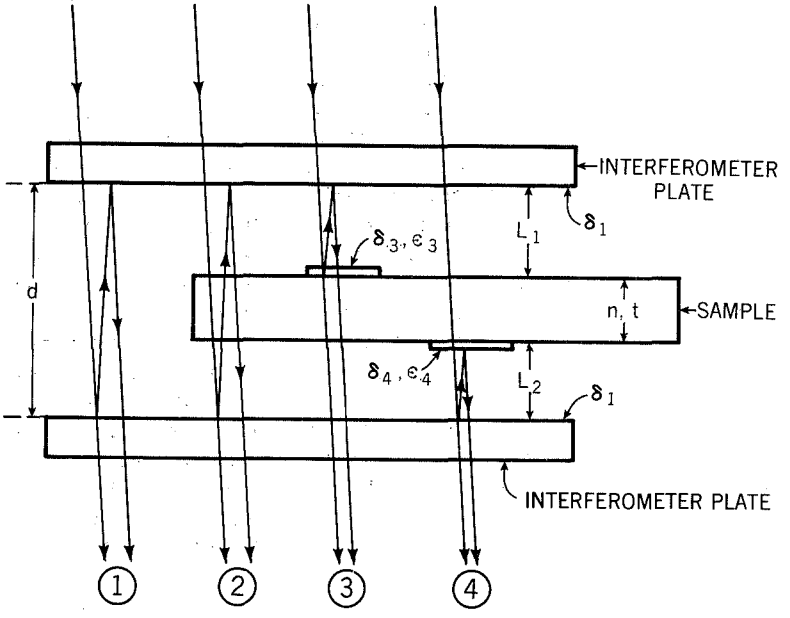

Figure 1. Schematic of Fabry-Perot Interferometer with Sample of Material to be Measured Inserted

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